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Carbon emission and sequestration of urban turfgrass systems in Hong Kong

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HIGHLIGHTS

- Carbon storage capacity at 0.05 to 0.21 kg C m^{-2} for grasses and 1.26 to 4.89 kg C m^{-2} for soils (to 15 cm depth).
- Turf maintenance contributed to carbon emissions at 0.17 to 0.63 kg Ce (carbon equivalent) m^{-2} y^{-1}.
- Turf system respiration was negatively correlated with soil carbon capacity but only in the wet season.
- Carbon stored in turfs could be offset by maintenance carbon emissions in 5–24 years.

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ABSTRACT

Climate change is more than just a global issue. Locally released carbon dioxide may lead to a rise in global ambient temperature and influence the surrounding climate. Urban greenery may mitigate this as they can remove carbon dioxide by storing carbon in substrates and vegetation. On the other hand, urban greenery systems which are under intense management and maintenance may contribute to the emission of carbon dioxide or other greenhouse gases. The impact of urban greenery on carbon balance in major metropolitan areas thus remains controversial. We investigated the carbon footprints of urban turf operation and maintenance by conducting a research questionnaire on different Hong Kong turfs in 2012, and showed that turf maintenance contributed 0.17 to 0.63 kg Ce m^{-2} y^{-1} to carbon emissions. We also determined the carbon storage of turfs at 0.05 to 0.21 kg C m^{-2} for aboveground grass biomass and 1.26 to 4.89 kg C m^{-2} for soils (to 15 cm depth). We estimated that the carbon sink capacity of turfs could be offset by carbon emissions in 5–24 years under current management patterns, shifting from carbon sink to carbon source. Our study suggested that maintenance management played a key role in the carbon budget and footprint of urban greeneries. The environmental impact of turfgrass systems can be optimized by shifting away from empirically designed maintenance schedules towards rational ones based on carbon sink and emission principles.

1. Introduction

Climate change has become a public concern in recent years (Jo, 2002). While many factors may contribute to climate change, greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have attracted much attention. The atmospheric concentrations of these GHGs have steadily risen during the last century (Lal, 2008), among which CO_2 has been considered a major factor for global warming and climate change in the same period (Jo, 2002).

Urban areas have become primary sources of air pollutants as well as GHGs (especially CO_2) due to high population densities, industrial activities, fossil-fuel combustion and infrastructure construction (Kaye et al., 2004, 2006). Urban activities release substantial quantity of carbon to the atmosphere, which amounts to as much as 80% of total CO_2 emissions (Awal et al., 2010; Churkina, 2008), and leads to increases in urban temperature as manifested in the phenomenal urban heat island (UHI) effect (Awal et al., 2010).

For esthetic and environmental reasons, urban areas, on the other hand, often contain greenery vegetation that can store carbon at different capacities (Davies et al., 2011; Jo, 2002, Jo and McPherson, 1995; Nowak and Crane, 2002). Consequently, urban greenery plays a critical and important role in mitigating climate change by offsetting some of the GHG emissions and provides benefits to the urban environment (Livesley et al., 2010; Susca et al., 2011). Apart from the conventional urban greenery, such as urban forests, parks, urban lawns, roadside greenery and golf courses, new types of greenery such as green roofs and green walls have become popular in lessening the environmental problems associated with urbanization and population growth, due to the limited spaces for greenery systems in dense urban areas (Getter and Rowe, 2006; Susca et al., 2011).

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Urban greenery typically consists of soil and vegetation. Soil serves as the substrate to provide support and nutrients for the plants, and as a relative long-term carbon sink (Getter et al., 2009; Jo, 2002), which plays an important role in the carbon cycle (Schlesinger, 1999; Schulze and Freibauer, 2005). Soil is the largest contributor to total carbon storage in urban area (Zhao et al., 2013). It is estimated that soil organic matter (SOM) stores about four times more carbon than the atmosphere (Lehmann et al., 2008), and about 300 times more than those released by burning fossil fuels (Schulze and Freibauer, 2005). On the other hand, annual carbon emission from soil is much greater than annual anthropogenic emission. Soil respiration emits CO_2 and is a major flux in the global carbon budget (Lovelock, 2008). However, urban soils have received much less attention than agricultural and forest soils, and even less on quantifying carbon storage and emission in urban turfgrass systems (Jo and McPherson, 1995; Pouyat et al., 2002, 2006; Townsend-Small and Czimczik, 2010). Previous studies on carbon storage have focused on the differences between land types (Pouyat et al., 2007, 2009), land conversion (Jackson et al., 2002) and land history (Ren et al., 2011). There are a few studies on carbon storage in urban greenery (Davies et al., 2011; Jo and McPherson, 1995; Qian and Follett, 2002) and carbon emissions from fertilizers and irrigation in urban lawns (Livesley et al., 2010; Zirkle et al., 2011). This study investigated the carbon storage and release of urban turfgrass systems using empirical data and determined the impact of maintenance in determining an urban lawn as a carbon sink or source.

2. Materials and methods

2.1. Site description

We studied selected urban turfs in Hong Kong (22°15′44″N, 114°10′41″E) and Shenzhen (22°32′43″N, 114°04′05″E), located in the coast of southern China, which have a monsoon-influenced humid subtropical climate, i.e. wet season from April to September and dry season from October to March. We focused on data collected during the wet season from August to September 2012, and dry season in January 2013.

We collected soil samples for carbon analysis from 14 urban turfs in Hong Kong and another 14 in Shenzhen, including park lawns, campus lawns, roadside turf and athletic fields with ages ranging from 2 to 55 years. We chose five urban turfs in Hong Kong (Table 1) for our study on carbon footprint due to maintenance based on access and representation. A and E were on the university campus, while B was an athletic (cricket) field. All these three turfs were newly established in 2010. C and D were from two urban parks which opened in 1988 and 1998 respectively. *Axonopus compressus* was the dominant turfgrass species in urban parks (C and D) and lawn A on the University campus, while *Zoysia* spp. dominated in the athletic field (B) and lawn E on campus with *Cynodon dactylon* × *C. transvaalensisn* also present in the athletic field.

2.2. Survey on the carbon footprint of turf maintenance

To estimate the carbon footprints associated with turf maintenance practices in terms of fertilization, irrigation and mowing, we conducted a questionnaire survey on turf maintenance for five urban turfs in Hong Kong in 2012 (Table 2).

We calculated total carbon emissions from turf maintenances (M_C, Eqs. (1)-(5)) using similar approach by Bartlett and James (2011) with carbon equivalent emission factors (Table 3, Lal, 2004) for different sources.

$$M_C = M_f + M_e + M_i + M_c \quad (1)$$

where M_C (kg Ce y^{-1}) was the carbon equivalent emission from turf maintenances, which was the sum of the carbon emission from fuel use (M_f), electricity use (M_e), irrigation (M_i) and chemical application (M_c), Eqs.(2)–(5).

$$M_f = C_f(F_m + F_c + F_o) \quad (2)$$

where C_f was the carbon equivalent emission factor of fuel sources (kg Ce L^{-1}); F_m was the amount of fuel used in mowing (L y^{-1}); F_c was the amount of fuel on chemicals application; and F_o was other source of fuel use.

$$M_e = E_{CLP} \times C_{CLP} + E_{HEC} \times C_{HEC} \quad (3)$$

where E_{CLP} and E_{HEC} were the amount of electricity consumption (kWh y^{-1}) in studied turfs. C_{CLP} (kg Ce kWh^{-1}) was the carbon equivalent emission factor for electricity purchased from CLP Power, derived from *CLP 2012 Sustainability Report*; while C_{HEC} (kg Ce kWh^{-1}) was derived from *HEC Sustainability Report 2012*.

$$M_i = W_i \times C_w \quad (4)$$

where W_i (m^3) was the amount of freshwater used for irrigation and C_w (kg Ce m^{-3}) was the carbon equivalent emission factor for freshwater, due to the electricity used for sewage processing (0.629 kWh m^{-3}, from Water Supplies Department of Hong Kong Annual Report 2011/12).

$$M_c = Q_{H,I,F}C_{H,I,F} + Q_{N,P,K}C_{N,P,K} \quad (5)$$

where $Q_{H,I,F}$ (kg y^{-1}) were the quantities of pesticide applied, including herbicides (*H*), insecticides (*I*) and fungicides (*F*), $C_{H,I,F}$ (kg Ce kg^{-1}) were the carbon equivalent emission factors for pesticides; $Q_{N,P,K}$ (kg y^{-1}) were the quantities of fertilizer application, including nitrogenous (N) fertilizers, phosphorous (P) fertilizers and potassium (K) fertilizers. $C_{N,P,K}$ (kg Ce kg^{-1}) were the carbon equivalent emission factors for -NPK fertilizers respectively.

Table 1
Sampling sites with grass species, lawn size, establishment year, and mowing and irrigation frequency.

Sites	Turfgrass species (coverage %)	Year of establishment	Lawn size (m^2)	No. of points sampled	Mowing frequency (times y^{-1})	Irrigation frequency (times y^{-1})
A	*Axonopus compressus* (100%)	2010	1020	9	21	636
B	*Zoysia matrella* (83%) *Cynodon dactylon* × *C. transvaalensisn* (17%) *Lolium perenne*[a]	2010	9000	15	130	60
C	*Axonopus compressus* (100%)	1998	1800	9	40	104
D	*Axonopus compressus* (70%) *Zoysia japonica* (30%)	1988	2500	15	12	104
E	*Zoysia japonica* (100%)	2010	2000	9	21	636

[a] Lolium perenne was planted in the dry season from November to March.

Table 2
Resource consumption for maintenance of urban lawns in Hong Kong.

Sites	Fuel use ($L\ y^{-1}$)			Electricity ($kWh\ y^{-1}$)	Irrigation ($m^3\ y^{-1}$)	Pesticides[a] ($kg\ y^{-1}$)			Fertilizer ($kg\ y^{-1}$)		
	Mowing	Chemicals application	Others			H	I	F	N	P	K
A	8 (G[a])	NA	NA	NA	1427	NA	0.5	1	10	10	14
B	400 (D[a]) 300 (G)	600(D)	200 (D) 40 (motor oil)	824	644	NA	2	22	10.8	2.2	25.4
C	100 (G)	NA	NA	350	936	NA	100	NA	250	25	250
D	25 (G)	NA	NA	NA	1300	NA	150	NA	NA	NA	NA
E	16 (G)	NA	NA	795	1654	NA	0.5	1	25	25	39

[a] G: gasoline; D: diesel; H: herbicide; I: insecticide; F: fungicide. NA: Data not available.

2.3. Soil sampling and analyses

We selected 9–15 points for soil sampling from 14 urban turfs in Hong Kong and 14 turfs in Shenzhen between 15 August and 27 September in 2012, and sampled soils from 0–5 cm, 5–10 cm to 10–15 cm with a soil core of 5 cm in diameter and 20 cm in depth, which were placed in plastic bags and delivered to the laboratory for analysis. We detected CO_2 flux from soil surface with grass cover using an EGM-4 gas monitor for CO_2 (CO_2 gas analyzer using non-dispersive, infrared gas analysis coupled with microprocessor based signal processing) with a soil respiration chamber (PP Systems, Amesbury, USA), and estimated turf system respiration rates, which included soil microbial and grass respiration, in urban turfs with 5–10 replicates for each site, during the wet season between August and September 2012, and dry season in January 2013.

We analyzed the chemical and physical properties for all soil samples. We weighed 100 g of the field-moist soil before and after drying in an oven at 105 °C for 48 h to determine water content (g H_2O g^{-1} dry soil). We determined soil carbon content with the oven-dried soil samples sieved by a 250 μm stainless steel mesh, which were then stored in glass vials in a desiccator before analysis. We adopted the method with combustion/non-dispersive infrared gas analyzer (Shimadzu TOC 5000A total organic carbon analyzer, Kyoto, Japan) to determine the concentrations of total carbon (TC), inorganic carbon (IC) and organic carbon (OC).

Table 3
Carbon emission coefficients for fuel, electricity, fresh water and chemical sources (Lal, 2004; WRI and WBCSD, 2005).

Items			Equivalent carbon emission (kg Ce $unit^{-1}$)
Fuel	Diesel		0.749 kg Ce L^{-1}
	Gasoline		0.650 kg Ce L^{-1}
	Motor oil (Lubricants)		0.763 kg Ce L^{-1}
Electricity	CLP[a]		0.210[b] kg Ce kWh^{-1}
	HEC[c]		0.215[d] kg Ce kWh^{-1}
Fresh water			0.132[e] kg Ce m^{-3} (CLP)
			0.136[f] kg Ce m^{-3} (HEC)
Chemicals	Fertilizer	Nitrogen fertilizer	1.30 kg Ce kg^{-1}
		Phosphorus fertilizer	0.20 kg Ce kg^{-1}
		Potassium fertilizer	0.15 kg Ce kg^{-1}
	Pesticides	Herbicide	6.3 kg Ce kg^{-1}
		Insecticide	5.1 kg Ce kg^{-1}
		Fungicide	3.9 kg Ce kg^{-1}

a CLP: CLP Power Hong Kong Limited.
b Carbon emission factor for electricity from CLP 2012 Sustainability Report (0.770 kg CO_2 kWh^{-1} = 0.770 × 12/44 kg Ce kWh^{-1}).
c HEC: Hong Kong Electric Company Limited.
d Carbon emission factor for electricity from HEC Sustainability Report 2012 (0.790 kg CO_2 kWh^{-1} = 0.790 × 12/44 kg Ce kWh^{-1}).
e, f Carbon emission factor for water consumption = Unit electricity consumption of fresh water (0.629 kWh m^{-3}, from Water Supplies Department of Hong Kong Annual Report 2011/12) × Power company – specific value (0.210[b] and 0.215[d] kg Ce kWh^{-1}) of purchased electricity.

We assumed that soil organic carbon (SOC) equals to TC for all soil samples with pH between 6.5 and 6.9, and calculated soil carbon density ($g\ m^{-2}$) according to Robertson et al. (1999).

$$SOC\left(g\ m^{-2}\right) = C\%\ x\ \rho_b\left(g\ cm^{-3}\right)x\ d\ (cm)x\ 10000\ cm^2/m^2 \tag{6}$$

where ρ_b is the bulk density ($g\ cm^{-3}$) of each soil layer and carbon concentration is expressed as weight-based percentage (%).

We used one soil core in each sampling site to determine bulk density (g soil cm^{-3}), which was calculated by dividing the initial volume by the oven-dry weight (105 °C for 48 h) of the sample.

2.4. Carbon stock in aboveground biomass of turfgrass vegetation

We collected the aboveground turfgrass shoots (25 × 15 cm^2) for carbon stock analysis at the same time with soil sampling at all turfs. We obtained the dry-weight biomass of the grass samples after oven drying at 105 °C for 48 h, and then cut and ground the samples to pass through a 60-mesh stainless steel sieve, which were stored in glass vials in a desiccator before carbon analysis. We used the TOC analyzer 5000A to determine the concentrations of TC, IC and OC in grass samples, and calculated the amount of carbon stock in grass by TOC concentration (%) multiplied by the dry weight of the sample, expressed in $g\ m^{-2}$.

2.5. Carbon budget of the whole turf

Carbon sequestration (S_C, kg C) by the whole turf is the sum SOC in soils (C_{soil}, kg C) and carbon stock in turfgrasses vegetation (C_{turf}, kg C).

$$S_C = S_{soil} + S_{turf}. \tag{7}$$

Total carbon budget (T_C) of the turf is the carbon emission from turf maintenances and carbon sequestration, given by Eq. (8):

$$T_{C=}S_C - M_C \times Y \tag{8}$$

where Y represents the years since the establishment of each turf; when the value of T_C is positive, the whole turf remains a carbon sink; if negative, the turf serves as a carbon source.

3. Results

3.1. Maintenance carbon emissions (MCE)

We obtained turf maintenance data (Table 2) from the turf managers, and combined with the conversion factors of carbon emission (Table 3) to estimate the total carbon footprints owing to turf maintenances as summarized in Table 4. We divided the emissions into three types: energy direct emissions (EDE), energy indirect emissions (EIE) and other indirect emissions. EDE is mainly from fuel use; EIE is carbon emission from electricity consumption; and other indirect emissions are those related to freshwater, pesticides and fertilizers. Based on the

Table 4
Carbon emissions due to turf management and maintenance in the studied turfs. Figures within brackets are emissions in percentage.

Sites	Equivalent carbon emissions (kg Ce y^{-1})[a]											
	EDE (fuel consumption)			EIE	Other indirect emissions (kg Ce y^{-1})							Total
	D[a]	G[a]	Other	Electricity	Freshwater	Pesticides[a]			Fertilizers			
						H	I	F	N	P	K	
A	NA	5.20 (2.4%)	NA	NA	188 (86.8%)	NA	2.55 (1.2%)	3.90 (1.8%)	13.0 (6.0%)	2.00 (0.9%)	2.10 (1.0%)	217 (100%)
B	899 (59.8%)	195 (13.0%)	30.5 (2.0%)	178 (11.8%)	87.3 (5.8%)	NA	10.2 (0.7%)	85.8 (5.7%)	14.0 (0.9%)	0.440 (0.0%)	3.81 (0.3%)	1504 (100%)
C	NA	65 (5.7%)	NA	73.6 (6.5%)	124 (10.8%)	NA	510 (44.8%)	NA	325 (28.5%)	5.00 (0.4%)	37.5 (3.3%)	1140 (100%)
D	NA	16.2 (1.7%)	NA	NA	172 (18.0%)	NA	765 (80.3%)	NA	NA	NA	NA	953 (100%)
E	NA	10.4 (2.3%)	NA	167 (37.5%)	218 (46.9%)	NA	2.55 (0.6%)	3.90 (0.9%)	32.5 (7.3%)	5.00 (1.1%)	5.85 (1.3%)	445 (100%)

[a] G: gasoline; D: diesel; H: herbicide; I: insecticide; F: fungicide. NA: Data not available.

amount of total carbon emissions, the turfs were categorized in terms of the level of maintenance.

A and E were recently established lawns (2010) on campus. For these two turfs, with less fuel used in mowing, and lower pesticide and fertilizer application, irrigation became the largest source of carbon emission. In A, 87% (188 kg Ce y^{-1}) carbon emission was from irrigation. Similarly, irrigation was the largest contributor to carbon emission, (218 kg Ce y^{-1}) in E, followed by electricity (167 kg Ce y^{-1}).

The two park lawns, C (1800 m^2) and D (2000 m^2), were established in 1998 and 1988 respectively. Less fuel was used for mowing, which contributed only 5.7% (65 kg Ce y^{-1}) and 1.7% (16.2 kg Ce y^{-1}) of the total carbon emissions respectively. The largest part of carbon emissions was from the application of pesticides and fertilizers. Insecticides were used at relatively high levels for both C (510 kg Ce y^{-1}) and D (765 kg Ce y^{-1}). The amount of fertilizers applied to C was 368 kg Ce y^{-1}, among which nitrogen fertilizer (325 kg Ce y^{-1}) was the most carbon intensive, followed by potassium fertilizer at 38 kg Ce y^{-1}, and phosphorus fertilizer at 5 kg Ce y^{-1}. Interestingly nitrogen fertilizer has been identified as the major source of GHG emissions in the playing area on golf courses (Bartlett and James, 2011), which aggravates the negative impact of such fertilizers on local climate.

B was a sports field with 9000 m^2 of *Zoysia matrella* (83%) and *Cynodon dactylon* × *C. transvaalensisn* (17%). There were several practices involving direct use of fuel under its high management and maintenances. Mowing was the most carbon intensive, with diesel (300 kg Ce y^{-1}) and gasoline (195 kg Ce y^{-1}) being utilized, which accounted for 33% of the total carbon emissions. Another major emission from fuel use came from application of fertilizers and pesticides, leading to comparable amount of carbon emission at 450 kg Ce y^{-1}. Fuel used by turf vehicles also emitted carbon at 150 kg Ce y^{-1}.

3.2. Carbon stock in soil and turfgrasses

We then determined the carbon sequestration capacity in soils and carbon stock in the aboveground biomass from these turfs. Soil pH was below 7.0 at all sites (Table 5), with values from 6.0 ± 0.5 to 6.9 ± 0.1 (S.E.) (n = 3). Soil water content was between 0.21 ± 0.01 and 0.27 ± 0.03 g H_2O g^{-1} dry soil and soil bulk density varied from 1.01 ± 0.05 to 1.51 ± 0.04 g cm^{-3} among all sites.

SOC levels decreased with soil depth at all sites for 0–15 cm (Table 5). This is consistent with the negative relationship between SOC and soil depth in urban areas reported by Edmondson et al. (2012). Similar pattern was also detected for SOC concentration for 23 turfs with different ages from 2 to 55 years old. Surface (0–5 cm) SOC concentrations showed different patterns for young turfs (≤30 years old) (Fig. 1a) and old turfs (42–55 years old) (Fig. 1b). We further divided the young turfs into two groups according to their SOC concentrations, seven turfs with high carbon (>2.0%) and nine turfs with low carbon (≤2.0). Surface SOC concentration increased with time in these two groups of young turfs, but decreased with time (R^2 0.649) in the old turfs. Golubiewski (2006) reported a positive correlation with soil carbon and site age of urban green spaces. In her study, SOC concentration was higher in soils 25 years or older than younger soils, but a shift in storage from belowground to aboveground occurs at 30–40 years after lawn construction.

We calculated the SOC sink capacity based on the SOC concentrations for these three soil depths, which showed very similar patterns, i.e., diminishing SOC sink capacities with increasing soil depth. The total carbon density of soil for 0–15 cm varied from 1.3 ± 0.19 to 4.9 ± 0.78 kg C m^{-2} (Fig. 2), which was slightly lower than those for 15 cm depth from turfs in the US (2.1 to 9.6 kg C m^{-2}) (Selhorst and Lal, 2013), and those for 10 cm depth in a botanical garden in Australia (2.5 to 6.4 kg C m^{-2}) (Livesley et al., 2010).

Our results showed that the carbon contents of the turfgrasses were between 40 and 45% of the dry biomass. When 40% was used to determine the carbon stored in turfgrasses for all sites, carbon density in turfgrass varied from 0.05 ± 0.00 kg C m^{-2} in *Zoysia matrella* and *Cynodon dactylon* × *C. transvaalensisn* to 0.21 kg ± 0.02C m^{-2} in *Axonopus compressus* (Table 6). The carbon density of herbaceous vegetation was 0.14 g C m^{-2}, which was the average value estimated at a citywide scale in Leicester, England (Davies et al., 2011). Carbon stock amount, taken into account of the lawn size, ranged between 163 ± 117 kg and 436 ± 129 kg among the turfs (Table 7).

3.3. Carbon budget of urban turfs

The net carbon budget includes maintenance carbon emissions (MCE) and carbon stored in soils and aboveground biomass of turfgrasses. The total amount of soil carbon storage (0–15 cm) of turfs varied from 2510 ± 371 to 27360 ± 2268 kg C, while the yearly carbon emissions due to turf maintenance ranged from 217 to 1504 kg Ce among all sites, which were less than the total carbon storage in all sites. Besides soil carbon storage, carbon stock in turfgrass also

Table 5
Soil properties and SOC content (%) in the upper 15 cm of the studied turfs. Standard errors of mean (n = 3) in parentheses.

Sites	pH	Water content (g H_2O g^{-1} dry soil)	Bulk density (g cm^{-3})	Soil C (%) (0–5 cm)	Soil C (%) (5–10 cm)	Soil C (%) (10–15 cm)
A	6.2 (0.4)	0.22 (0.03)	1.51 (0.04)	2.98 (0.56)	2.25 (0.12)	1.34 (0.40)
B	6.9 (0.1)	0.21 (0.01)	1.38 (0.05)	2.77 (0.40)	0.88 (0.72)	0.77 (0.35)
C	6.0 (0.5)	0.27 (0.03)	1.01 (0.05)	3.76 (0.49)	1.13 (0.30)	0.91 (0.32)
D	6.5 (0.3)	0.22 (0.01)	1.21 (0.06)	1.66 (0.13)	1.21 (0.17)	0.17 (0.09)
E	6.3 (0.2)	0.26 (0.01)	1.17 (0.04)	1.16 (0.19)	0.54 (0.17)	0.44 (0.25)

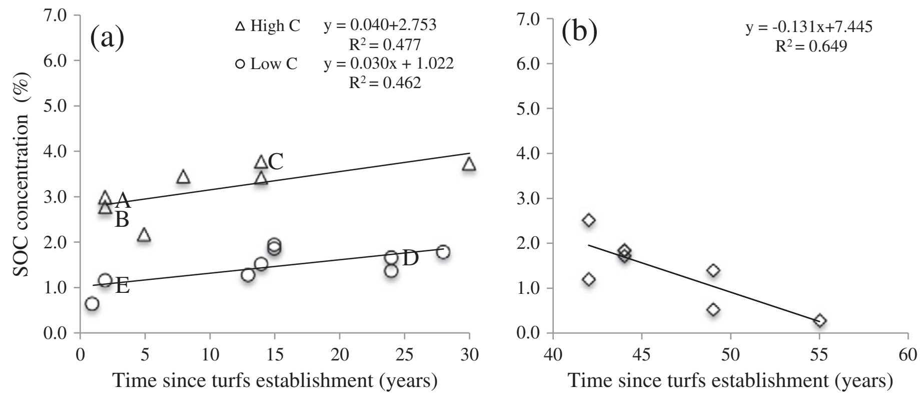

Fig. 1. SOC concentrations in surface 5 cm soils in urban turfs with different ages (3 replicates for each sample) (A, B, C, D and E in Fig. 1a represent Turf A, B, C, D and E respectively).

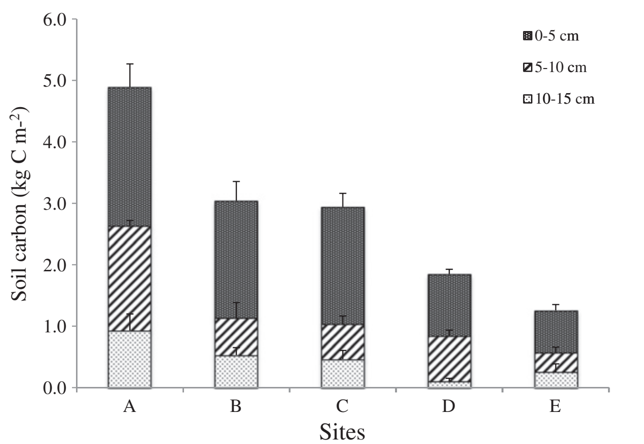

Fig. 2. Soil carbon sink capacity in the studied turfs. Error bars are standard errors (n = 3).

contributes to carbon sequestration. With the assumption that carbon stock in soil and turfgrasses was stable, and the maintenances of each turf were the same for every year since its establishment, it took approximately 5 to 24 years (Table 7) for the carbon storage to be offset by maintenance carbon emissions under current management. With reference to the age of the turfs, three turfs remained as carbon sinks while the other two turfs (C and D) had already shifted from carbon sink to carbon source.

4. Discussion

In this study, we showed that operations and maintenance contribute a very significant part of the carbon emission for urban turfs. While the carbon stock in soil and aboveground biomass remain relatively stable over years, it is the practice of turf management that may ultimately decide whether the turf is a net emitter or sink for CO_2. Thus, we propose that a rational design of maintenance schedule should be implemented for each turf based on its carbon stock and functional purposes to achieve a net carbon budget beneficial to the environment.

Interestingly, our study showed that turfs remained as carbon sinks for much shorter time in our study than the estimated 66 to 199 years for home lawns by Selhorst and Lal (2013). It is worth pointing out that in their study, the carbon cost from lawn maintenance including mowing and fertilizer use was 0.025 kg C m^{-2} y^{-1}, which was one magnitude lower than the MCE (0.17–0.63 kg C m^{-2} y^{-1}, Table 6) we obtained for our turfs. In contrast, Zirkle et al. (2011) showed that all home lawns serve as carbon sinks based on the amount of carbon storage in urban soils, carbon fixed and sequestrated by grasses, and the carbon footprint of lawn management and maintenance practices. On the other hand, it has been reported that newly established golf courses could become carbon sources from carbon sinks with large amount of carbon emissions from the maintenance practices in 30 years (Selhorst and Lal, 2011). Further studies may be needed to reconcile the differences between our studies and those mentioned above.

One area that needs further attention is soil respiration. Although an important source for carbon emissions, soil respiration was not included in our estimation of the carbon budget of the turfs. While we monitored turf system respiration rates (g CO_2 m^{-2} h^{-1}) before mowing in the wet and dry seasons with the CO_2 analyzer (EGM-4), which included both soil respiration and plant foliar respiration. We felt that the data obtained were not enough for scaling up to annual CO_2 flux. Nevertheless, turf system respiration rates decreased with the increase in soil carbon density among the sampling turfs in the wet season (Fig. 3). The same pattern was not obvious in the dry season in 2013 (from 0.67 ± 0.02 to 1.40 g ± 0.07 CO_2 m^{-2} h^{-1}), which was much lower than those in the wet season (1.18 ± 0.04 to 3.21 ± 0.10 g CO_2 m^{-2} h^{-1}) probably due to the lower plant productivity in the dry season. It would be valuable to incorporate soil respiration data into carbon budget and re-evaluate not only our own results, but also those reported previously (Selhorst and Lal (2013).

Table 6
Maintenance carbon emission (MCE) rates and carbon density in soil and aboveground dry biomass (AGB) of turfgrass in growing season. Standard errors of mean (n = 3) in parentheses.

Sites	Turfgrass species (growing season)	Turfgrass AGB (kg C m^{-2})	C density in grass (kg C m^{-2})	Soil C density (kg C m^{-2})	Total C density (kg C m^{-2})	MCE (kg Ce $m^{-2}y^{-1}$)
A	*Axonopus compressus*	0.39 (0.04)	0.16 (0.02)	4.89 (0.78)	5.05	0.21
B	*Zoysia matrella*	0.12 (0.01)	0.05 (0.00)	3.04 (0.25)	3.09	0.17
	Cynodon dactylon × *C. transvaalensisn*					
C	*Axonopus compressus*	0.53 (0.04)	0.21 (0.02)	2.94 (0.37)	3.15	0.63
D	*Axonopus compressus*	0.19 (0.01)	0.08 (0.01)	1.85 (0.05)	2.62	0.38
	Zoysia japonica					
E	*Zoysia japonica*	0.51 (0.08)	0.20 (0.03)	1.26 (0.19)	1.46	0.22

Table 7
Carbon stock in soil and above-ground biomass (AGB) of turfgrass and maintenance CO_2 emissions (MCE).

Sites	C stored in soil (kg C)	C stored in AGB (kg C)	Total C stored (kg C)	MCE (kg C y^{-1})	Years (Ce = Cs)	Turf age	Net C budget
A	4986 (790)	163 (117)	5149	217	24	3	C sink
B	27,358 (2268)	436 (129)	27,794	1504	18	3	C sink
C	5292 (668)	378 (129)	5670	1140	5	15	C source
D	4618 (115)	193 (49)	4811	953	5	25	C source
E	2509(371)	407 (209)	2916	445	6	3	C sink

5. Conclusion

Our study suggested that the carbon footprint of turf maintenances such as mowing, irrigation, application of fertilizers and pesticides, and other operations can be manipulated. For example, mowing, which uses fuel and is the most carbon intensive maintenance, should be carried out less often without compromising the quality of the turf or with more efficient technologies such as solar-powered devices to reduce carbon emission. Similarly, green technologies should be applied for more efficient watering and chemical application to reduce carbon emission. On the other hand, urban soil served as a carbon sink while management practices remained the major source of carbon emissions. Since the carbon emission increased with age, the turfgrass systems could shift from carbon sink to carbon source in just a few years. Thus, one can certainly try to replace the turf which may renew the carbon sequestration capacity of the turfs. Nevertheless, with better understanding of the behavior of urban greenery in terms of carbon balance, it may be possible to design or replace current turf systems in urban areas that remain a carbon sink, and prevent the observed shift from sink to source in the near future.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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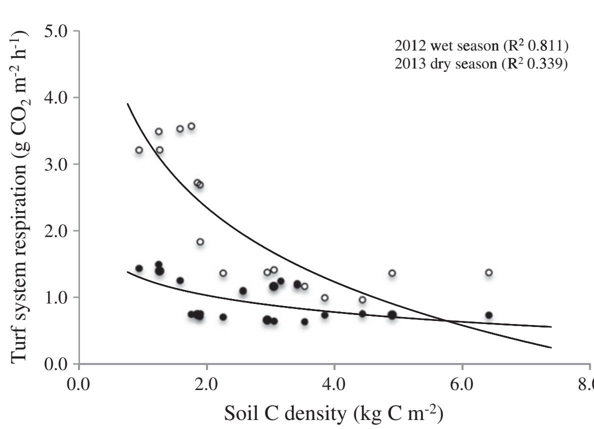

Fig. 3. Turf system respiration rates (g CO_2 m^{-2} h^{-1}) and its correlation with soil carbon density in turfs in wet season 2012 and dry season 2013.

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